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GUIDANCE^{AND} HOMING OF MISSILES^{AND} PILOTLESS AIRCRAFT

A Report of the AAG Scientific Advisory Group

by

H. L. DRYDEN

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I. A. GETTING

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Guidance and Homing **OF MISSILES AND PILOTLESS AIRCRAFT**

A REPORT PREPARED FOR THE AAF
SCIENTIFIC ADVISORY GROUP

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PART IV

RADAR HOMING MISSILES

INTRODUCTION

Much attention has been devoted during the present war to the development of guided missiles, which are intended automatically to seek out a target or "home" on the target. Such a missile must utilize some physical property of the military target which causes the target to stand out from the background. The most commonly suggested property is the emission or reflection of electromagnetic radiation, and homing systems of control have been developed for the three major divisions of the electromagnetic spectrum, popularly described as light, heat, and radio. The report by Dr. G. A. Morton, entitled "Heat and Television Guided Missiles," page 35, reviews the state of development of the light- and heat-seeking missiles, and the present report describes the general principles, problems, and state of development of radar homing.

As indicated by the title, radio waves of very short wavelength (ten centimeters or less) give the most useful technical results in missiles because the scale of the apparatus required to intercept or direct the energy into beams is of the same order as a small multiple of the wavelength. Likewise the techniques used in radar, in particular the transmission in short pulses of energy rather than continuously, are particularly useful in solving the problems of target selection and discrimination. Thus the radio-homing device invariably uses microwaves and usually microwave-radar techniques.

GENERAL PRINCIPLES OF OPERATION

Since military targets, with the exception of enemy radar transmitters, do not emit radio waves, it is necessary to illuminate the target with radio waves if a radio homing method is to be used. In a pulsed radar system the transmitter consists of a high-power oscillator capable of emitting radio waves of the desired wavelength from an antenna system. A modulator or pulser causes the transmitter to emit electromagnetic waves in the form of short pulses or wave trains of high intensity. To give some quantitative idea, one of the systems to be described emits 2000 pulses/sec of waves having a length of about 10 cm. The duration of the emission at each pulse is 0.7 microsec. Since a wavelength of 10 cm corresponds to a frequency of 3000 mcps,

each pulse or wave train contains about 2250 waves extending over 22,500 cm or about 740 ft. Since the pulses are 500 microsec apart, the wave trains are separated in space by 93 miles.

The emitted energy is focused into a beam by the directional properties of the antenna system. While the wave train is of constant thickness in the direction of travel, it continually spreads in directions at right angles to the direction of travel. When the emitted energy strikes any object, some of the energy is scattered or reflected and a very small fraction travels back toward the transmitter and can be detected and measured by a sensitive receiver. Since every object returns some reflected or scattered energy, the study of the return of energy from various types of targets is basic for the design of successful radar-homing systems.

The energy returned from the target is detected and measured by a suitable sensitive receiver. In order to be useful in guiding a missile, the information must be in the form of directional data, preferably in quantitative form. To obtain directional data the homing device must be directionally sensitive. Usually the receiving antenna for a missile homing device has axially symmetrical directional characteristics produced by a spherical or parabolic reflector. The response of the receiver is greatest when the axis of the antenna is pointed directly at the target. While this property could be used to determine when the target is on the axis for steady signals, there is no discrimination between right and left or up and down and fluctuations of signal intensity cannot be distinguished from changes in intensity produced by changes in direction. The usual practice is to scan the field of view by moving the antenna axis and to commutate or phase the received signal intensity with the scanning. The on-course indication then becomes an equality of two signals and a directional sense is provided. Furthermore, most of the effects of signal fluctuation are eliminated by scanning at a reasonably rapid rate. The scan rate in present equipment is of the order of from 30 to 40 cps. Conical scanning is used; i. e., the axis rotates in a cone so that the receiver effectively looks up, right, down, left, in succession. The output is switched automatically by a commutator to the up, right, down, and left channels of two differential amplifiers which supply the up-down and right-left control signals.

The use of pulsed radar permits the selection of a definite target which will be described later in greater detail. In principle, if the receiver is kept insensitive at all times except for a brief period of time which begins at a definite time interval following the emission of a pulse, energy will be received only from those objects lying at a fixed range, i. e., those for which the transit time from transmitter to object to receiver equals the interval between the emission of the pulse and the increase of receiver sensitivity. To be specific, if the receiver is increased in sensitivity 50 microsec after the emission of a pulse, only objects where the total distance from transmitter to object to receiver is 9.3 miles will contribute energy to the receiver output. Since the total distance changes as the missile approaches its target, some method of automatically varying the time interval must be used to track the target in range.

In order to be useful a homing control must be operative at a reasonable distance from the targets of interest. As the missile approaches the target, the received energy will vary by as much as a billion fold or more. Hence the receiver must be provided with an automatic gain control to decrease its sensitivity as the received energy increases.

TYPES OF SYSTEMS

Three types of systems have been given attention, differing only in the location of the transmitter, the receiver always being in the missile. The transmitter may be an enemy transmitter, a transmitter illuminating the target but not carried by the missile, or a transmitter carried by the missile. The nomenclature is not standardized. The first type has generally received the code name "Moth," the second "RHB" or "Pelican," the third "SRB" or "Bat." German scientists who conceived but did not complete the development of similar systems referred to them as passive, half-active, and active radio-homing methods. The general locations of missile and target for a glide bomb released from an aircraft are indicated in Figs. 1, 2 and 3.

A simplified block diagram of the RHB or Pelican equipment, as installed in a glide bomb released from an aircraft is shown in Fig. 4. A block diagram for Moth would be identical except that the target selector and rear view antenna would be omitted. Provision is made for supplying external power from the carrying aircraft through the umbilical cord. This cord also carries circuits for supervising the operation of the equipment before release, for remote tuning of the receiver, and for selecting and locking on a target, these circuits terminating at the airplane control and indicator station.

The umbilical cord is connected by a pull-away connector to the missile junction box. Before release the equipment is switched to the internal battery which with the power supply furnishes all the necessary voltage for the receiver and other units. The energy returned from the target passes from antenna to receiver to target selector. The output of the target selector operates the automatic gain control of the receiver and is passed through the commutator to a differential amplifier which furnishes signals to the autopilot.

As the missile approaches the target, the transmitted pulse directly received from the transmitter decreases. The energy received from the target increases and the automatic gain control accordingly decreases the sensitivity of the receiver. Sufficient energy had to be received from the transmitter in the original design of the Pelican equipment to synchornize the target-selector circuit, and it was found necessary to add the auxiliary rear view antenna which is indicated on the block diagram. A later development accomplished synchronization from a special oscillator in the missile and the rear view antenna was eliminated.

A simplified block diagram of the SRB or Bat equipment, as installed in a glide bomb released from an aircraft is shown in Fig. 5. The new elements added are the transmitter, modulator, and the TR tube for switching from transmitter to receiver so that the same antenna can be used for both. Synchornization is accomplished by direct connection from the transmitter. Otherwise the simplified block diagrams are identical.

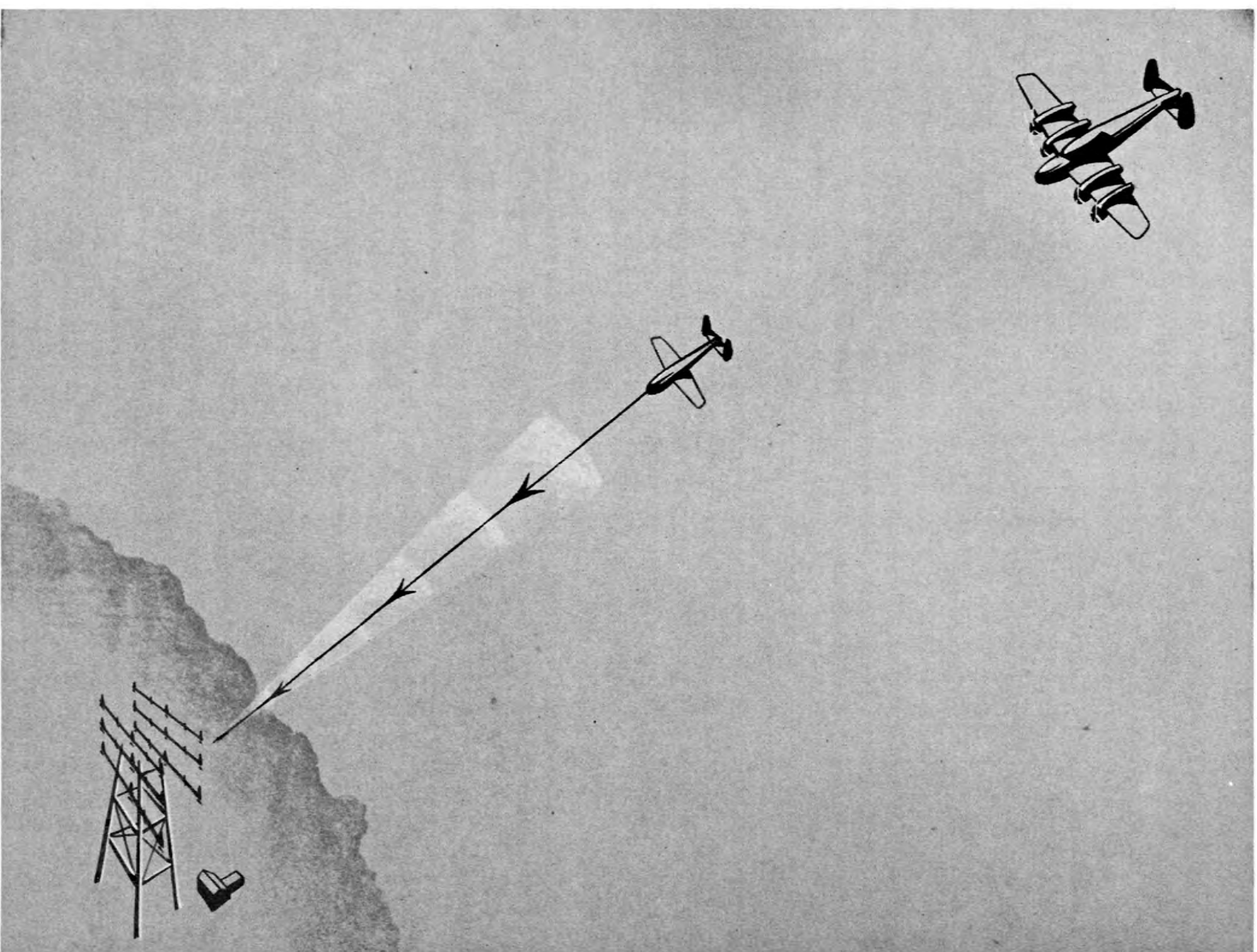


Figure 1 — Moth

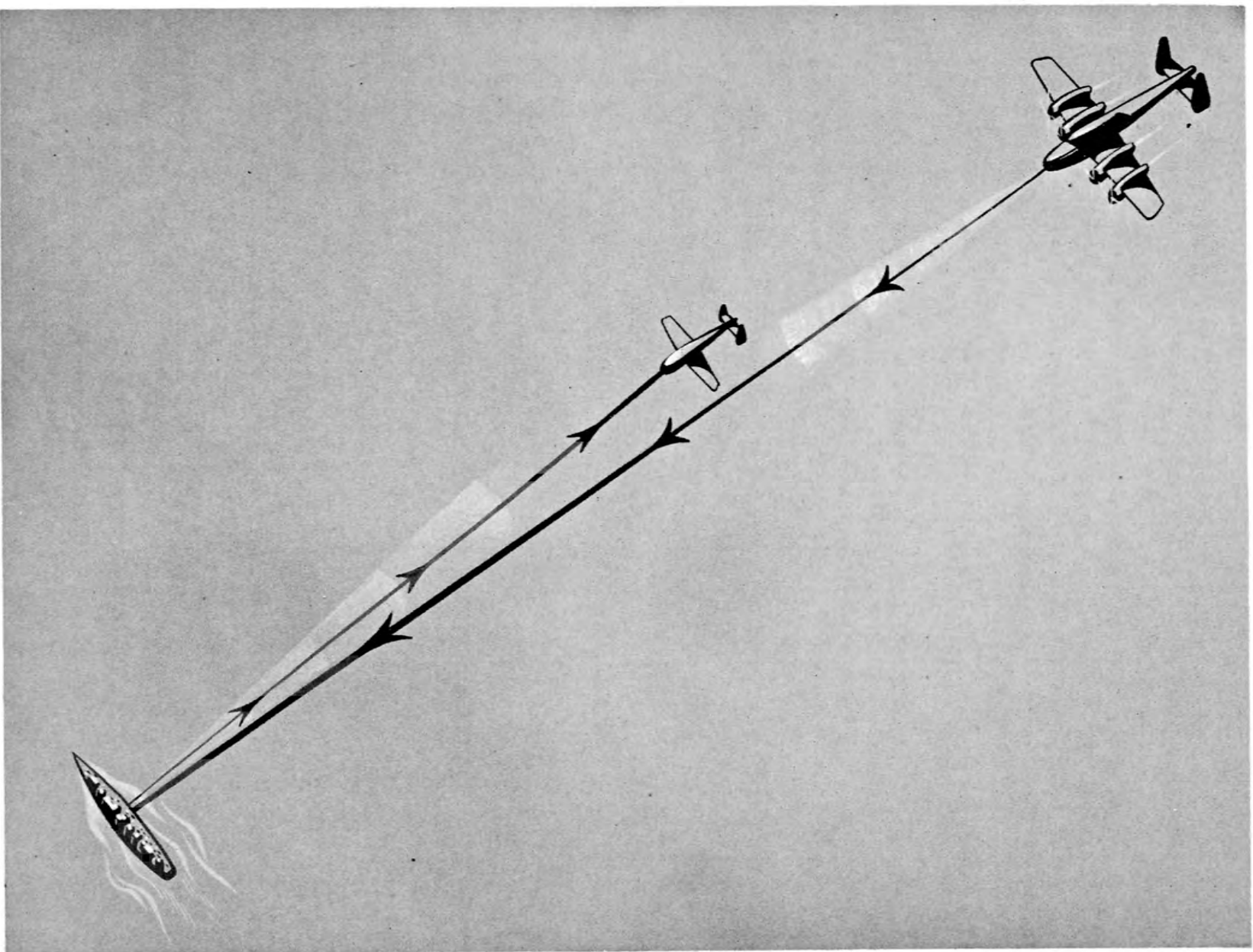


Figure 2 — RHB (Pelican)

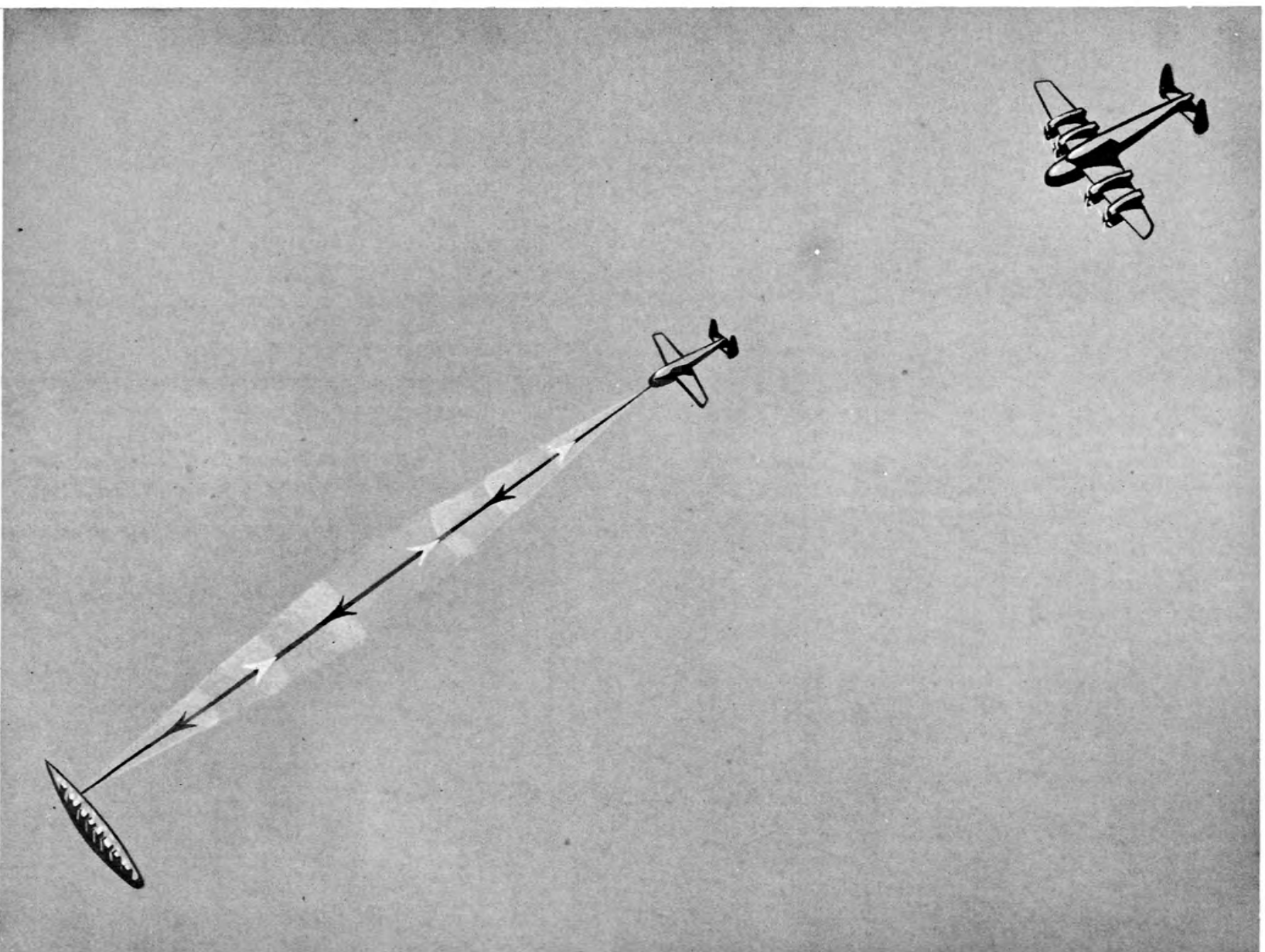


Figure 3 — SRB (Bot)

AIRPLANE CONTROL
& INDICATOR STATION
EXTERNAL POWER

UMBILICAL CORD

PULL-AWAY CONNECTOR

BATTERY

POWER
SUPPLY

MISSILE
JUNCTION
BOX

AUTO PILOT



ANTENNA

RECEIVER

TARGET
SELECTOR

COMMUTATOR

UP
DOWN
LEFT
RIGHT

DIFFERENTIAL
AMPLIFIER

GATED
AUTOMATIC
GAIN CONTROL

REAR VIEW ANTENNA

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Figure 4 — Block Diagram of RHB (Pelican)

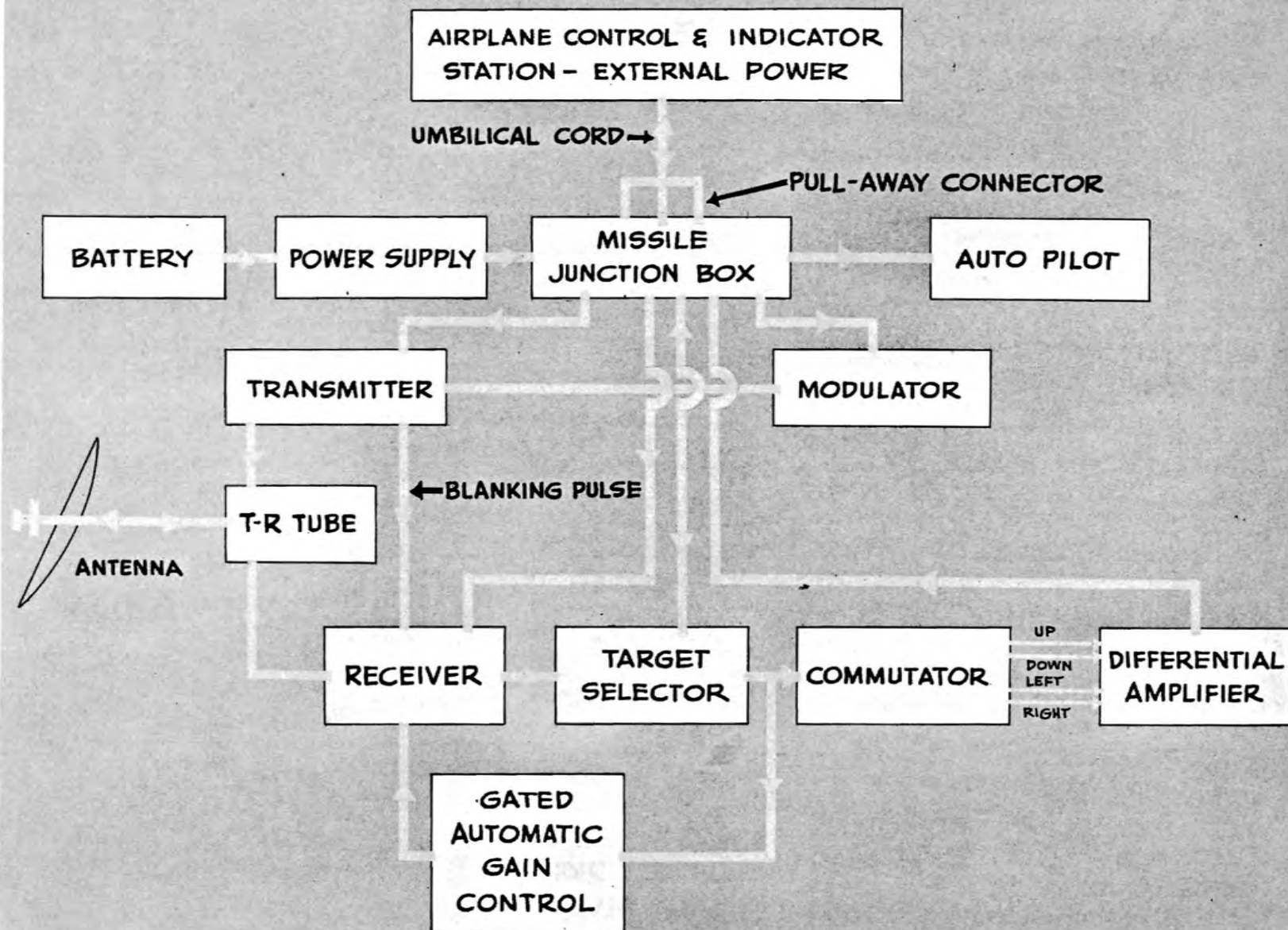


Figure 5 — Block Diagram of SRB (Bat)

PROPAGATION AND TARGET PROPERTIES

Microwaves travel without serious loss of energy through ordinary clouds and fog; hence, radar-homing devices are effective through overcast and at night. The propagation of microwaves is quasi-optical in character. They are not reflected to an appreciable degree by the Kennelly-Heaviside layer, and they do not spread far beyond the horizon by diffraction. Around small obstacles the waves spread appreciably by diffraction and they are usually scattered by rough surfaces such as the ground. The surface of the sea is, however, a good reflector especially near grazing incidence. Water vapor in the atmosphere may produce refraction effects.

Any ordinary solid or liquid substance is capable of returning radio energy. Depending on size and shape of the object in relation to the wavelength, the process may be one of reflection or scattering. No method is known of making an object of complicated shape invisible to radar, although special coatings have been developed which reduce the return from large flat surfaces. Radar reflections from most objects have some of the characteristics of optical reflections of the sun from the earth as observed from aircraft, in that small changes of position of the receiver may produce large changes in energy received corresponding to the kaleidoscopic high lights from window panes, pools of water, etc. Radar reflections from ships and aircraft show similar fluctuations.

Ordinarily there will be many objects at the same range and although a military target reflects radio waves, the reflected energy or echo from the desired target may be lost in a background "clutter" of unwanted echoes. This is especially true for land targets since the usual irregularities of the ground insure the presence of many echoes. Even for sea targets such as ships, the surface of the water, especially in high winds, reflects energy to a receiver. Only in the case of aircraft targets viewed from below is the unwanted background energy negligible.

The distinguishing features of an individual echo are very few. In very special cases there may be a characteristic relation between the polarization of the incident and reflected waves and in some situations moving targets may be isolated from stationary targets. The most favorable situations for the application of radar-homing missiles are those in which there are only a few targets and in which the energy returned from these targets is substantially greater than that from the ground or sea at the same range. Hence, the primary application of radar-homing missiles to date has been against ships.

In connection with the Pelican and Bat projects, numerous studies have been made of the reflection of microwaves from ships. These studies have shown that the energy returned from a given target and from the sea varies within wide limits and is a function of the angle of illumination and surface conditions. The energy returned from the ship targets constantly decreases as the angle of illumination and reception increases,

whereas that returned from the sea constantly increases. Comparative tests were made with a Pelican receiver on microwaves of approximately 10-cm wavelength of the energy received at various depression angles when the target was illuminated from a distance at depression angles of from 2° to 11°. These tests showed that nearly all of the energy scattered from the ship appears between the sea and 45° above the incident beam and that the return is fairly uniform over 180° in azimuth on the illuminated side of the target. A receiver which picks up signals at 20 miles and has adequate return for automatic tracking and homing at 10 miles can no longer obtain an adequate signal for tracking or homing at one mile when the depression angle at the receiver is 70°.

A more complete study was made for wavelengths of about 3 cm. The energy returned was expressed in the form of the cross-sectional areas of a sphere which would return the same energy as the target. If the received power at range r is P_r as measured with a receiving antenna of effective area A_r when the peak transmitted power is P_t , the gain of the transmitting antenna is G_t and the transmitter is at range r_2 , the cross-sectional area S_a of the equivalent sphere is defined by:

$$S_a = \frac{16\pi^2 r_1^2 r_2^2 P_r}{P_t G_t A_r} \quad (1)$$

The values of S_a for the return from the sea measured with transmitter and receiver at the same location varied through the ranges indicated below as a function of depression angle:

<i>Depression Angle</i>	<i>Cross-Sectional Area of Equivalent Sphere in Sq Ft</i>	
40°	7 to	1,500
50°	15 to	1,600
60°	200 to	16,000
70°	4,000 to	64,000
80°	250,000 to	640,000
90°	40,000,000 to	100,000,000

The values of S_a for ships ranging in size from LST to Liberty ships as a function of depression angle were as follows:

<i>Depression Angle</i>	<i>Cross-Sectional Area of Equivalent Sphere in Sq Ft</i>	
20°	10,000 to	100,000
30°	10,000 to	100,000
40°	10,000 to	65,000
50°	1,000 to	20,000
55°	250 to	10,000

It is seen that the target becomes lost in the sea return at depression angles of 50° to 60°. Because of fading, automatic-tracking circuits may have difficulty at depression angles as low as 35° to 45° even when the average power in the preceding table appears adequate.

Other studies made on microwaves of 10-cm wavelength show cross-sectional areas of the equivalent sphere of the same order of magnitude. For design purposes the value of S_a for a large ship of high gain may be taken as 23,000,000 sq ft, for an average Liberty ship 500,000 sq ft, and for a very small ship 20,000 sq ft if viewed at depression angles of the order of 10°. The average reflected power is found to increase inversely as the fourth power of the range when transmitter and receiver are at the same range as indicated by the formula previously given. This relation was checked

experimentally to within 800 ft of large ships. However, the power at a given distance may vary through wide limits, i.e., by a factor of as much as 100 times in some cases for runs on apparently similar targets.

The values of S_a for aircraft targets are naturally much smaller than for ship targets. For a large bomber S_a is of the order of 1000 sq ft. For small aircraft or missiles S_a is considerably smaller.

While studies are known to be in progress on land targets with respect to the practicability of radar-homing missiles, detailed results are not yet available. It is known that there are some target situations in which radar homing is feasible, but more research is needed.

DETECTION

The energy returned from the target is detected and measured by a superheterodyne receiver. The receiver contains a tunable local oscillator in the form of a velocity-modulated or Klystron tube with associated cavity which generates microwaves whose frequency can be adjusted to differ by a fixed amount, the beat or intermediate frequency, from the frequency of the radio waves to be received. In the Pelican equipment the intermediate frequency is 30 mcps; in the Bat, 60 mcps. The received energy and that from the local oscillator are applied to a crystal mixer the resulting output echo signals being at the intermediate frequency. These signals are amplified by a multistage amplifier tuned to the intermediate frequency but with a sufficient bandwidth to transmit the short pulses without large distortion. A detector tube passes the envelope of the pulses. These signals are designated "video" signals. After amplification and passage through a control gate amplifier, which is made operative at the proper time by the target-selector circuit, the signals pass to the directional control unit. The general operation of these units will be described later.

The amount of energy available to the receiver from an incoming signal is proportional to the effective areas of the receiver antenna. If the antenna is in the form of a dipole or other receptor at the focus of a reflector of diameter D , the effective area of the antenna is $\frac{\pi D^2}{4}$. Thus a large antenna enables the detection of smaller signals better than does a small antenna.

The background of random noise in the receiver sets a lower limit to the intensity of signal which can be detected. If the radar receiver were perfect, the noise would be determined solely by the bandwidth of the receiver and the absolute temperature of the system, being in fact equal to $KT\Delta f$ where K is a universal constant (1.372×10^{-23} joules per degree C). T is the absolute temperature and Δf the receiver bandwidth. For a bandwidth of 10 mcps and an absolute temperature of 325°C the noise intensity in a perfect receiver would be 4.4×10^{-14} w. Any actual receiver gives N times as much noise where N is called the over-all noise figure and is about 10 for modern receivers. The receivers used in radar-homing equipment now available and in production will

usually detect signals of 10^{-12} w; but a target giving such small signals will not operate the tracking circuits satisfactorily.

DIRECTIONAL INFORMATION

The video signals which pass from the control gate amplifier are extremely short pulses spaced far apart in time as compared with their duration; for example, in the Bat equipment 0.7 microsec pulses 500 microsec apart. As a result of the conical scanning of the antenna, the amplitudes vary unless the target is on the axis of rotation of the antenna. For small angular displacements of the target, the modulation is approximately sinusoidal at the scanning frequency which in present equipment is about 30 cps. Thus there are about 67 pulses for each scanning cycle. As shown in Fig. 6, the amplitude and phase of the modulation measure the amount and direction of the target position with reference to the axis of rotation of the antenna.

The narrow, widely spaced pulses contain insufficient energy to operate controls. They are first passed to a rectifier or demodulator which acts as a pulse stretcher, giving an output consisting of the 30-c envelope on which is superimposed a pulse frequency ripple. The signal is then subdivided by the commutator, as indicated in Fig. 7, into four parts corresponding to the four quadrants of the antenna scan. The up-down and the right-left signals proceed to differential amplifiers which compare the signals from the opposite commutator segments and smooth the result to give an approximately DC output proportional to the angle off course.

The method of obtaining directional information which has been described is that exemplified in available equipment. It is inherently a comparison of the amplitudes of signals obtained successively from two slightly different directions. The results may be falsified by fluctuations in the echo occurring in the 0.017 sec required to move the antenna to the two directions. Future development of this general method will almost certainly use much higher scan rates, probably obtained wholly by electrical means, and will probably use simultaneous lobe-comparison methods. Not only can the effects of fading be reduced, but also the time lags in furnishing directional information to the controls of the missile can be greatly reduced.

TARGET DISCRIMINATION

The first main problem in the design of any homing missile is the determination of the method or methods to be used for discriminating between the desired target and others which may be present. The directional characteristics of the transmitting and receiving antennas permit a certain degree of selection. Within the field of view determined by these directional characteristics, the target giving the greatest echo will normally control.

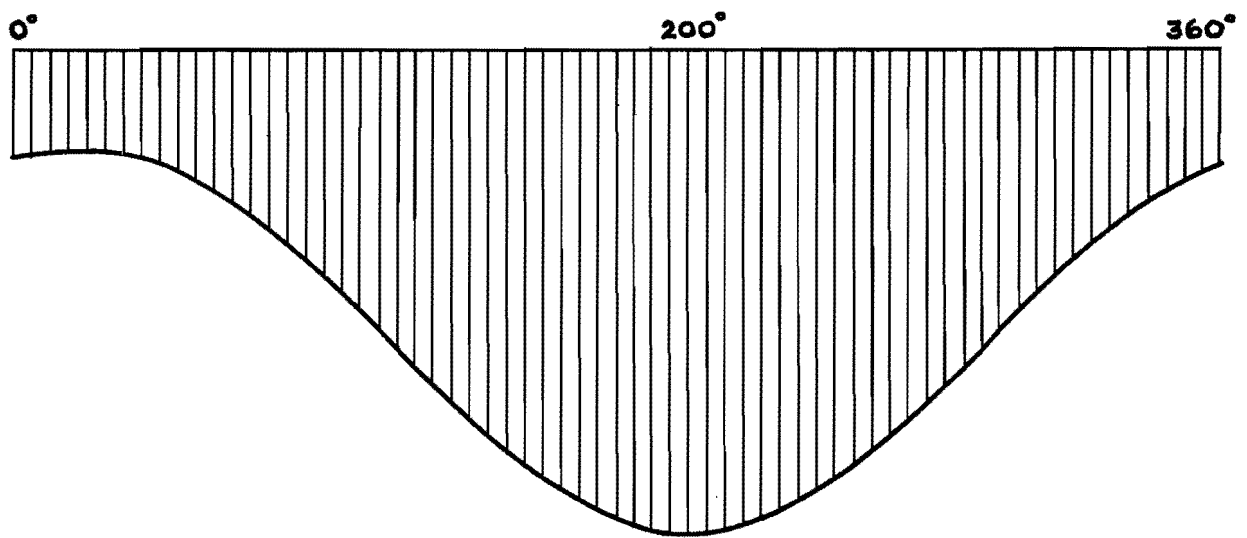
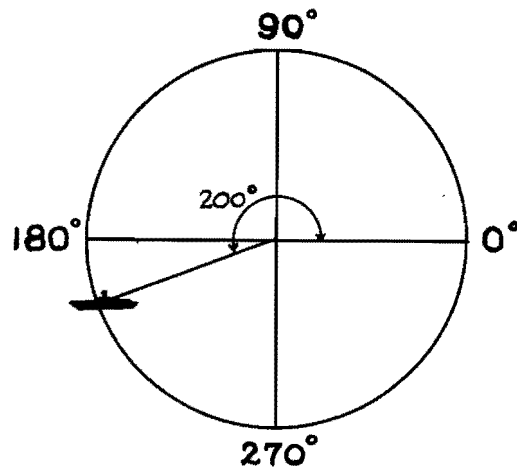


Figure 6 — Conical Scanning Process

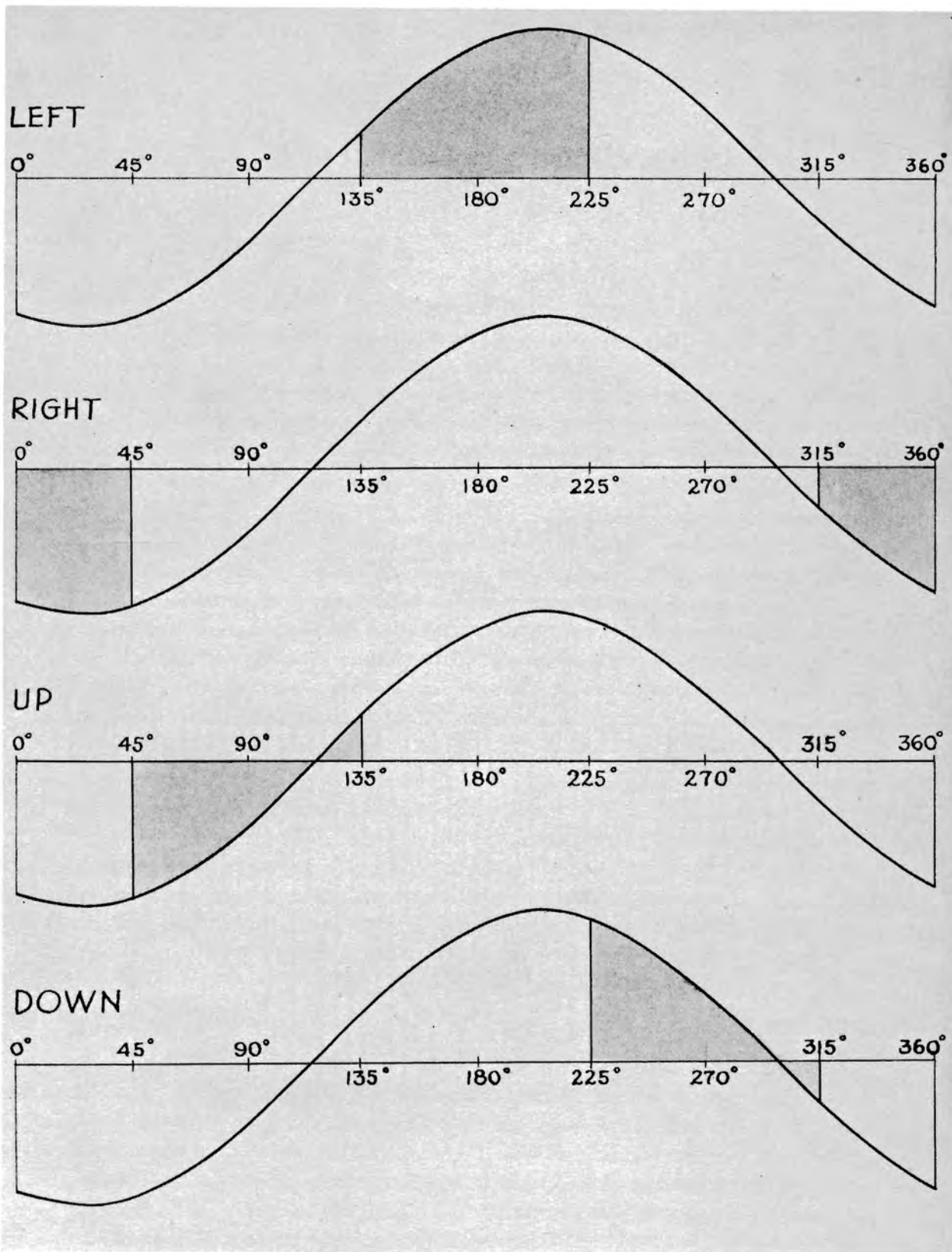


Figure 7 — Commutation of Scanned Signals

However, it is not technically feasible to use extremely narrow beams, first, because the antennas cannot be made sufficiently large in comparison with the wavelength, and second, because a narrow field of view would require the motion of the missile to be controlled to an impractical degree.

In a homing system using a pulsed illuminating beam, another method is most useful, namely, a range-selection method. By making the receiver sensitive only for a short period of time at a definite time interval following the emission of a pulse by the transmitter, signals will be received only from targets at a selected range, since the selected time interval is the time of transit from transmitter to target to receiver. As the missile approaches the target, the time interval must be shortened, i.e., the target must be automatically tracked in range. Likewise since the time measurement must start with the emission of a pulse, the transmitter and receiver must be synchronized in some manner.

Range discrimination is essential in radar-homing missiles launched from aircraft because of the large amount of energy returned from the ground or sea, one of which is always the biggest target in the field. At ranges of the order of five miles or more, and with antennas of the smaller sizes required for missiles, as much energy is received from the ground or sea directly below as from an average target. This first signal is known as "altitude" signal and must be excluded from the receiver. In glider missiles the altitude is always less than the range to the target, and hence the range selector makes possible elimination of the altitude signal. In ground-to-air missiles with receiver only (RHB), there is no "altitude" signal but in air-to-air missiles at ranges greater than the altitude or ground-to-air SRB missiles, the range to the target and to the ground will sometimes coincide and special measures will have to be taken to prevent a switch from homing on the target to homing on the altitude signal.

The functions of the target selector are: (1) to "gate" the signal from the desired target, i. e., allow the differential amplifiers to receive information only at the exact time that the signal from the desired target is received; and (2) to adjust the time of operation of the gate circuit to the range of the target, i. e., to track the target in range. The gating operation must be synchronized with the transmitter. The general methods used in present equipment will be briefly discussed.

When the transmitter and receiver are in the missile a synchronizing pulse is obtained very simply by a direct connection to the pulse transformer of the transmitter. When the transmitter and receiver are separated another method must be used. So far two have been developed. The older uses the directly received signal from the transmitter as the synchronizing impulse. Precautions must be taken to insure that sufficient energy is received. When the target is illuminated from an aircraft, the missile may not remain within the beam because of evasive action of the aircraft or because of the difference in the speeds of the missile and aircraft. Hence the transmitter must be equipped with an additional nondirectional or at least a very broad-beam antenna to insure the radiation of some energy in the direction of the missile. Likewise the directional characteristics of the receiver antenna are such that little energy is received from the rear which is the direction of the transmitter. It is necessary, therefore, to provide a rear view antenna on the missile to insure that sufficient energy is received directly from the transmitter to synchronize the range-selection gate.

The second system derives its synchronization from the reflected signal and hence the equipment is termed self-synchronous. Actually a very stable low-frequency oscillator is built into the receiver and an identical oscillator is used to control the pulse rate of the transmitter. The frequency of the receiver oscillator is automatically adjusted to that of the received pulse rate. The self-synchronous RHB was developed primarily because it offered a means of securing homing intelligence all the way into the point of impact with the target. Both the Pelican and the Bat experience difficulties at close ranges because of the coincidence of the initial pulse with the returning echo. The Pelican requires the reception of the direct-transmitted pulse for synchronization, and the Bat cannot make use of the echo when its transmitter is operating. The self-synchronous RHB, however, derives its synchronization from the echo only and it can exclude the initial pulse which is transmitted from many miles behind the receiver. A few experimental models of radar-homing equipment with this method of synchronization have been built and tested.

The gating operation by which the receiver is made receptive to the target echo is accomplished by applying a square-wave negative impulse of about one micro-second duration to the cathode of the control-gate amplifying tube which has its grid normally biased well below cutoff, but which is made operative while the gate is applied. The formation of the gate is initiated by the synchronizing pulse from the transmitter or synchronizing oscillator being applied to the grid of a variable time-delay pulse generator, which is a multivibrator adapted to give only one cycle of operation. The rapid change of voltage at the end of the square wave formed by the multivibrator is used to form the time-delayed pulse. This output pulse is applied to a blocking oscillator which in turn generates the range-selector gate pulse of one microsecond duration. The latter pulse is used to sensitize the control amplifier tubes. The proper time delay required to make the gate from the blocking oscillator coincide with the returning echo is determined by the voltage applied to a control grid of the multivibrator, either by a manual adjustment when initially selecting a target or from the automatic range-tracking circuit.

The final function of the target selector is to track the target in range as the missile approaches the target. The nature of the methods used will be illustrated by that used in the Bat equipment. After leaving the video amplifier, the echo signals are applied to an artificial delay line which has three output taps so that for every echo signal applied to the input three echoes, designated early echo, control echo, and late echo, appear in order separated in time by about 0.27 microsec. The echoes so spaced are fed separately to the grids of three amplifier tubes, all of which are biased below cutoff. These same tubes are gated simultaneously by the range-selector gate pulse. If the range-selector gate is centered on the control echo, the signals passed by the early and late echo amplifiers will be equal. If the gate is early, the early echo signal will be larger than the late echo signal, whereas if the gate is late, the late echo signal will be larger. (See Fig. 8.) These early and late echo signals are used in succeeding stages of the target-tracking circuits to control the variable time-delay pulse generator so that the gate moves at the speed corresponding to the changing range of the target. Circuits are also included which cause the gate to continue to move at nearly the correct speed even if the received signals should fade for a few seconds. If the signal fades for a longer time, it may not be in the gate when it reappears because the gate speed is not

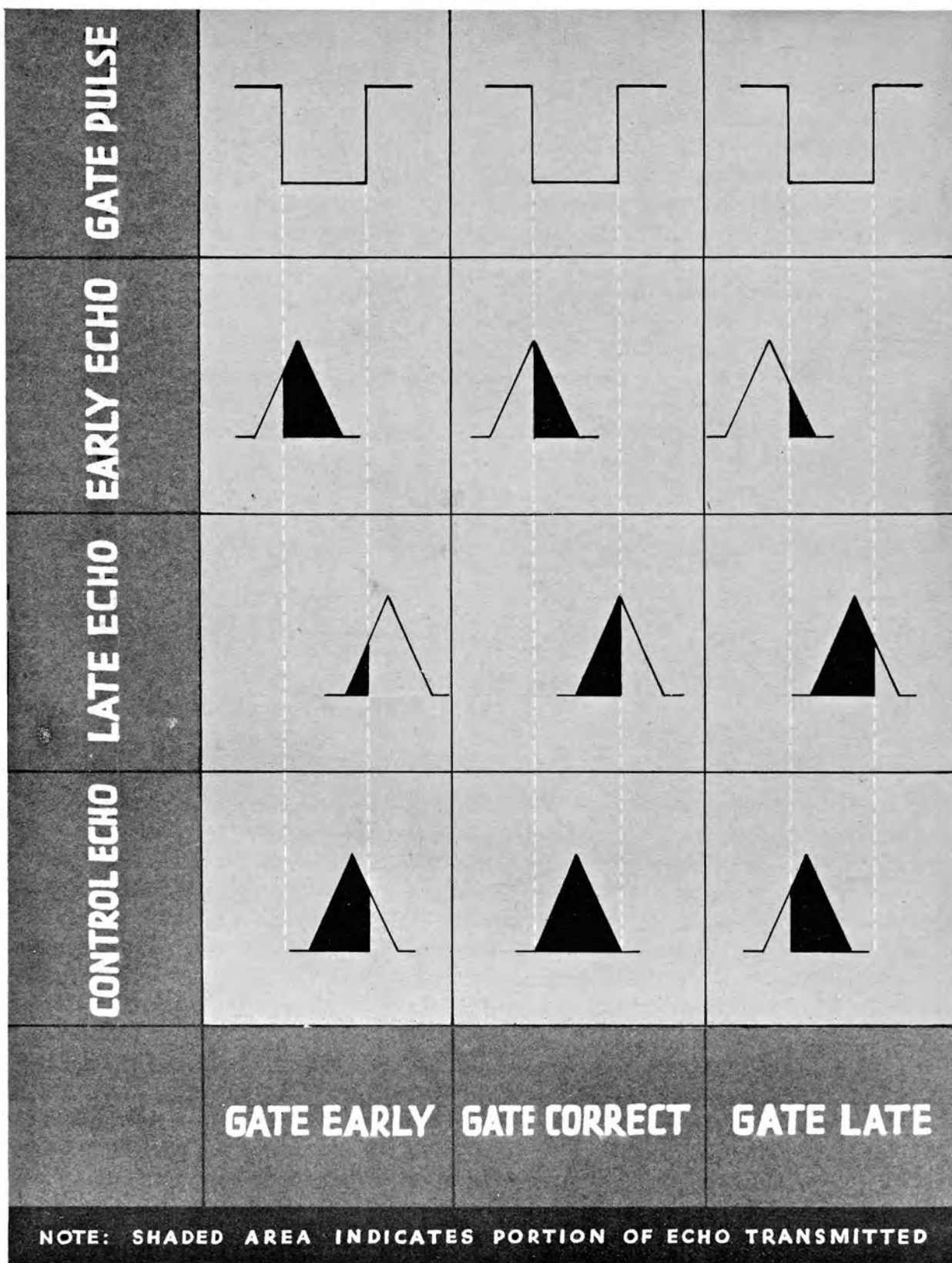


Figure 8 — Principles of Tracking in Range

accurately that of the target. In this case the target is lost and the gate will lock on the next echo entering it. Since the gate is only 0.7 microsec wide, the selector can distinguish between targets within about 750 ft of each other in range.

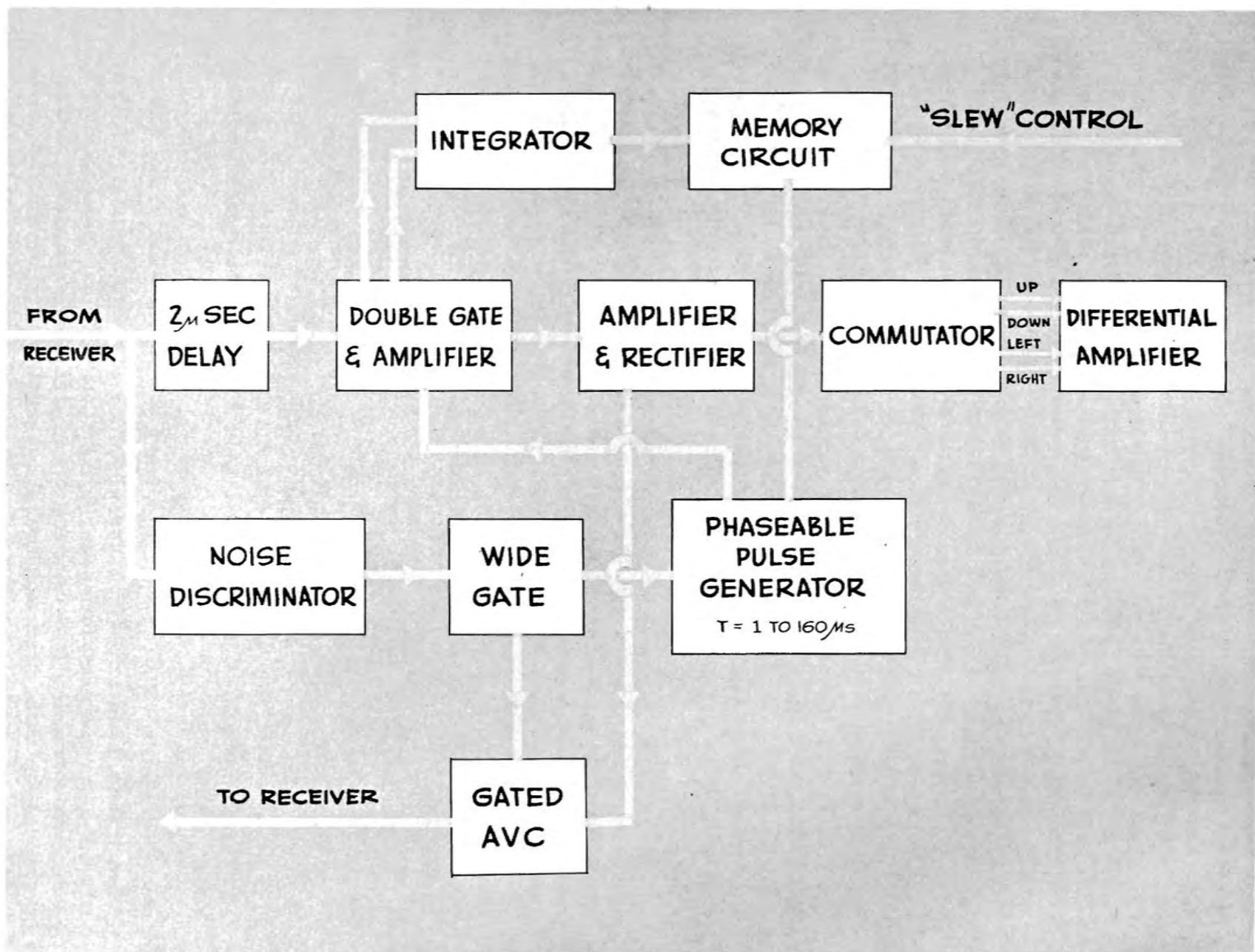
For tracking purposes the Pelican target selector uses one echo and a delay line to form an early and a late gate rather than a single gate and an early and delayed echo, but the general principles are otherwise identical. A simplified block diagram of the Pelican target selector is shown in Fig. 9. The video signals pass through a two-microsec delay line, thence through the double-gated amplifier to an amplifier and rectifier, to commutator, to differential amplifier. The formation of the gating pulse is accomplished in precisely the same way as just described for the Bat, except that it is initiated at the reception of the direct signal from the transmitter which enters a noise discriminator. This is a tube so biased as to prevent initiation of the gates by noise or weak interference but to permit entry of the stronger synchronizing pulse. As soon as the initial pulse is received it operates a single-cycle multivibrator which gates the noise discriminator to prevent any other signals from entering the timing circuits until after the echo has been received. A square gate is taken from this multivibrator to apply the automatic gain control which will be discussed later. As with all the radar-homing equipments the control-gate pulse can be manually adjusted or locked on the desired target before release by application of a "slewing" voltage through the connection indicated which runs through the umbilical cord to the airplane control station.

AUTOMATIC GAIN CONTROL

The energy returned from a target increases by more than a billion fold (10^9) as a missile carrying its transmitter and released at extreme range travels toward a large target. The average receivers available will just detect a signal of 10^{-12} w. With transmitters of moderate power and fairly wide beams, the maximum observed power return from a large ship on close approach is about 10^{-2} w. Directional information of satisfactory quality must be supplied over this enormous range (90 to 100 decibels), and an automatic control of the sensitivity of the receiver is required. It has in fact proved difficult to provide a range of more than about 70 decibels in the automatic gain control itself, and the problem of a completely satisfactory automatic gain control for homing against targets from long ranges cannot be regarded as solved to complete satisfaction.

The automatic gain control must not be made so fast in action as to obscure the 30-c modulation which gives the directional information. It is so adjusted that a strong signal will be held to half the overload value of the video-output stage and thus the full modulation of the echo due to the scanning will be passed without distortion.

The automatic gain control operates from the output of the control-gate amplifier so that the sensitivity is controlled only by variations in signal from the target on which the gate is locked. The gain control operates by adjusting the grid or plate voltage of certain of the tubes of the intermediate-frequency amplifier.



In the case of the RHB system, receiving its synchronization from the transmitted beam, it is necessary to prevent the operation of the automatic gain control on the direct transmitted pulse. When the transmitter and receiver are together (as in the Bat), however, a synchronizing pulse can be obtained through a direct wire connection. For considerations of range tracking very close to the target the initial pulse is held down as much as possible. Not only is the automatic gain control applied, but a special blanking pulse is added to early stages of the intermediate-frequency amplifier. Since the transmitter is always immediately adjacent to the receiver, the initial pulse can only be blanked out with difficulty. In the case of the Pelican carrying only the receiver, it is necessary to keep the receiver fully sensitive until the initial pulse is received and then to apply the automatic gain-control voltage. A pentode tube gated by the positive square wave of the wide-gate multivibrator, which is shown in Fig. 9, provides the proper gain-control voltage to the grids of the intermediate-frequency amplifier stages. The sensitivity of the receiver is thus reduced by action of the wide gate for a period of approximately 300 microsec to a value determined by the level of the target signal on which the target selector is locked.

Since in the Pelican the transmitter remains nearly at a fixed distance, the energy returned increases inversely as the square of the distance of the missile from the target, whereas in the Bat the energy returned increases inversely as the fourth power. Thus the required range of operation of the automatic gain control is less for the Pelican than for the Bat on the assumption that control must be retained to within the same distance of the target.

The receivers now available begin to show effects of overload when the received energy amounts to about 10^{-5} w. The effect of overloading is to decrease the directional sensitivity, although for some receivers the decrease may be preceded by a region of increased sensitivity as the power level is increased. The directional sensitivity is measured by the output current for a given angle of course. As the power level is increased the directional sensitivity falls to zero. With further increase the receiver begins to give a reversed signal, i.e., in a direction to move the missile away from the target. It is obvious that overloading must be avoided if accuracy is to be obtained.

RANGE

The range of radar-homing equipment can be determined from the standard radar range formula:

$$r_1^2 r_2^2 = \frac{P_t G_t A_r S_a}{16\pi^2 P_r} \quad (2)$$

where r_1 is the distance from transmitter to target, r_2 is the distance from receiver to target, P_t is the peak transmitted power, G_t is the gain of the transmitter antenna, A_r is the effective receiver area, S_a is the cross-sectional area of the sphere which reflects the same energy as the target, and P_r is the minimum power required to operate the receiver.

Since $G_t = \frac{\pi^2 D_t^2}{\lambda^2}$ where D_t is the diameter of the "dish" on the transmitting antenna and λ is the wavelength, and $A_r = \frac{\pi D_r^2}{4}$ where D_r is the diameter of the "dish" on the receiving antenna, the range formula may be written

$$r_1^2 r_2^2 = \frac{\pi P_t D_t^2 D_r^2 S_a}{64 P_r \lambda^2} \quad (3)$$

The peak powers of the transmitters used in Pelican and Bat equipment are of the order of 30,000 and 8,000 w respectively. The diameter of the receiver antenna reflector used in the missile is 1 ft and we shall make illustrative computations for $\lambda = 1/3$ ft. The value of receiver power P_r depends on the magnitude of the fluctuations of the target echo and on the factors of safety desired. While a signal of 10^{-12} w can be detected, it is necessary to have a signal of 10^{-10} w for reliable tracking in view of fluctuations of the signal. We shall therefore assume $P_r = 10^{-10}$. In the case of the Pelican, the transmitter is on the launching aircraft and may be equipped with a larger reflector, for example, $D_t = 2.5$ ft. For the Bat, the same antenna is used for transmitting and receiving, i.e., $D_t = 1$ ft. In both Pelican and Bat, the transmitter and receiver are at the same distance at the release point; hence $r_1 = r_2 = r_o$. Introducing these values, we find

$$\text{for Pelican} \quad r_o^4 = 8.28 \times 10^{14} S_a \quad (4)$$

$$\text{for Bat} \quad r_o^4 = .353 \times 10^{14} S_a \quad (5)$$

Hence, Pelican gives a range of $\sqrt[4]{\frac{8.28}{.353}}$ or 2.2 times that of Bat, due mostly to the larger reflector on the transmitter and to some extent to the somewhat larger transmitted power.

We have previously seen that S_a ranges from 2×10^4 sq ft for small ships to 2×10^7 sq ft for very large ships when viewed at small depression angles. Hence, for these extremes the ranges are as follows: for Pelican, 12 miles and 68 miles; for Bat, 5.5 miles and 31 miles. for a Liberty ship S_a is about 5×10^5 sq ft which corresponds to a range of 27 miles for Pelican and 12 miles for Bat.

COUNTERMEASURES

An important consideration in the use of any automatic homing device is its susceptibility to countermeasures. It will never be possible to claim that any given radar-homing device is proof against jamming. But there are several reasons why this fact does not make radar-homing devices useless.

The most common method of jamming is to fill the receiver with continuous wave radiation of frequency very near the transmitter radar frequency. A beat frequency with the target echo signal is set up in the receiver and directional information

is lost. The method requires a knowledge of the frequency and a reasonably accurate adjustment of the jamming transmitter. Unless the jamming transmitter tracks the missile and concentrates its energy in a beam, the power required becomes very high. If the missile contains transmitter and receiver, the target signal increases as the inverse fourth power while the jamming signal increases only as the inverse square of the distance from target to missile. In view of the short time of flight of a missile, and of the possibility of using several missiles simultaneously on different frequencies, the task of the jammer is not simple. Moreover decoy methods could be used by the attacking aircraft, such as illuminating the target with search radar at frequencies not used on the homing missile. If the enemy finds means to counter these tactics, the missile could be equipped with an automatic frequency shifting device to change suddenly the frequencies of the radar transmitter and receiver equally and simultaneously every few seconds. Or more simply, the missile could be equipped with an automatic switching device to cause it to home on the jamming transmitter.

A more effective countermeasure against radar-homing missiles is the use of decoy targets such as corner reflectors towed on barges behind ships which are possible targets. The decoy targets must be close enough so that range discrimination by the radar-homing device is not possible. The use of such decoys would be a great nuisance to ships and the destruction of the decoy targets by an early attack would leave the ship exposed to later missiles.

The use of radar-controlled gunfire might be effective against a few missiles but the simultaneous release of a sufficient number of missiles on different courses would probably saturate the defenses.

Maneuvering of the target is another possible countermeasure, but it is probable that computers will soon be available which will make such a countermeasure ineffective.

EQUIPMENT AVAILABLE AT PRESENT

The radar-homing equipment now available was developed in its essential features by the Radiation Laboratory of the Massachusetts Institute of Technology at the request of the Army and Navy. Further engineering development was directed by a special group recruited from the Radiation Laboratory and set up under contract with Division 5, National Defense Research Committee, as an M.I.T. field station at the National Bureau of Standards, Washington, D. C. Here under one roof a cooperative organization was set up to develop radar-homing missiles, consisting of a National Bureau of Standards civilian group operating as the Washington Project of Division 5, NDRC, the M.I.T. field radar group, and the Bureau of Ordnance Experimental Unit of the Research and Development Division, Bureau of Ordnance, Navy Department, made up of officers and enlisted men of the U. S. Navy. Engineers of the Zenith Radio Corporation, of Bell Telephone Laboratories, and of the Western

Electric Company cooperated in the development of production equipment under contract with the Navy.

A brief description will be given of the Pelican (RHB) equipment of Navy designation SWOD Radio Receiver Mark 1, Mod 3, built by the Zenith Radio Corporation and of the Bat (SRB) equipment of Navy designation SWOD Radar Mark 2, Mod 1, built by the Western Electric Company. Detailed descriptions are given in bulletins prepared by the manufacturers. The reports of the M.I.T. field radar group contain more additional information relative to certain desirable modifications to give improved performance, and to service test equipment.

The SWOD Radio Receiver Mark 1, is shown in Fig. 10. The complete system consists of spinner antenna, receiver unit, blower, junction box, rear antenna, power supply, and battery. Using a 14-v storage battery weighing 37 lb and providing full-load power for approximately 30 min, the total weight is 126 lb. The approximate weights and over-all dimensions of the principal components are as follows:

<i>Component</i>	<i>Weight (lb)</i>	<i>Approximate Dimensions (in.)</i>
Spinner Antenna	11	19 x 19 x 17
Receiver Unit	28	17 x 16 x 7
Blower	1	
Junction Box	7	19 x 9 x 5
Rear Antenna	3	
Power Supply	34	14 x 9 x 9
Battery	37	11 x 9 x 5
Cables	5	

The spinner antenna consists of a horizontal dipole mounted at the focus of a paraboloid reflector 12 in. in diameter having a focal length of 3.6 in. In front of the dipole is a much smaller flat reflector. The radiation pattern is about 30° wide and the spinning reflector is offset by 5.5° in order to displace the axis of the pattern by 11° from the axis of rotation. As the reflector is rotated the axis of the radiation pattern describes a cone having a vertex angle of 22°.

The receiver unit contains the local oscillator (a 2K28 reflex Klystron tube), the crystal mixer, the 30-mcps intermediate-frequency amplifier of 3-mcps bandwidth, the synchronizing and gate generating circuits, the double gate and amplifier, the target-selector and tracking circuits, the automatic gain control, and the differential amplifiers.

The blower is a thermostatically controlled fan to circulate air in the receiver compartment if the temperature in this compartment rises above 70°F.

The junction box provides a central distributing point and contains the lower half of the breakaway connector between the missile and the carrying aircraft. It also contains a time-delay switch to prevent the application of electrical intelligence for a period of 3 sec to permit the missile to clear the aircraft safely.

The rear antenna consists of three half-wave dipoles arranged circularly around the central coaxial feed line, thus giving nondirectional characteristics.

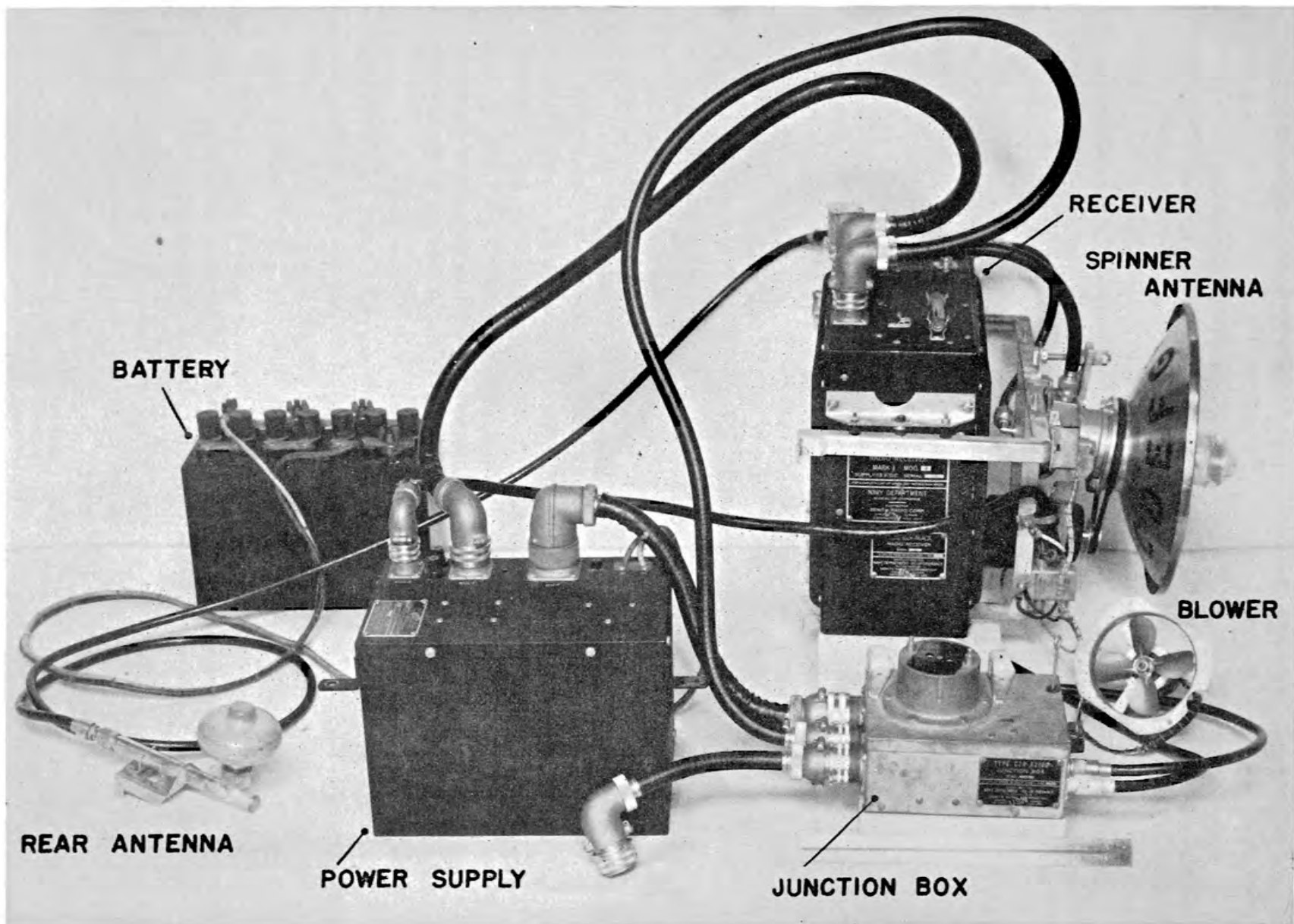


Figure 10 — SWOD Radio Receiver Mark 1

The power supply contains the dynamotor which furnishes the high DC voltages required by the receiver unit. It also contains a motor-driven potentiometer to provide repeller voltage for tuning the local oscillator in the receiver by remote control from the aircraft control station.

The SWOD Radio Receiver Mark 1 is designed to operate with a standard AN/APS-2 search radar. This equipment emits about 800 pulses/sec, each of about 1-microsec duration. The peak power is about 30 kw and the antenna reflector is 30 in. in diameter.

The SWOD Radio Receiver Mark 1 will just detect a signal of 10^{-12} w and saturates at about 10^{-5} w. A signal of 10^{-10} w is required for satisfactory tracking and operation of the automatic gain control. The response begins to drop off at power levels higher than 10^{-4} w. The loss is preceded by an abrupt increase in sensitivity over a small range in power. For moderate overloads the effect of overload is a loss of directional information, but for large overloads the receiver gives error signals of the wrong sign.

The SWOD Radar Mark 2, Mod 1, is shown in Fig. 11. The complete system consists of a nose assembly, power supply unit, inverter, and batteries. The total weight is 216 lb. The approximate weights and over-all dimensions of the principal components are as follows:

<i>Component</i>	<i>Weight (lb)</i>	<i>Approximate Dimensions (in.)</i>
Nose Assembly (with Plastic covering)	75	36 x 22 x 23
Power Supply Unit	36	22 x 20 x 9
Inverter	26	12 x 9 x 7
Batteries (two 14-v)	74	10 x 11 x 9
Cables	5	

The nose assembly consists of the antenna assembly, the transmitter-receiver, and the target-selector and directional-control assembly. The same antenna is used for transmitting and receiving. It is a half-wave dipole fed by a coaxial line. The dipole is at the focus of a 12-in. paraboloidal reflector. In front of the dipole is a small semicylindrical reflector to intercept the nonfocused forward radiation. The beam is about 21° wide. The offset angle and the method of conical scanning are the same as for the SWOD Radio Receiver Mark 1.

The transmitter is modulated by a free-running blocking oscillator feeding an 807 amplifier which triggers two 1B29 gas tubes. These tubes operate into a pulse-forming line, thence into a 3-1/2 to 1 step-up transformer which excites the 2J39 magnetron. The output of the magnetron is fed by a coaxial line into a 721B TR switching tube in the antenna line. The peak power radiated is from 6 to 10 kw. The pulse width is about 0.7 microsec and the pulse rate is variable from 1900 to 2100 cps. The synchronizing pulse for the target selector is obtained from a third winding on the magnetron coupling transformer.

The receiving system consists of a superhetrodyne receiver using a crystal mixer and Shepard-Pierce 726A local oscillator. The intermediate frequency is 60 megacycles with a bandwidth of about 4 mcps for 6 decibels down. The maximum ampli-

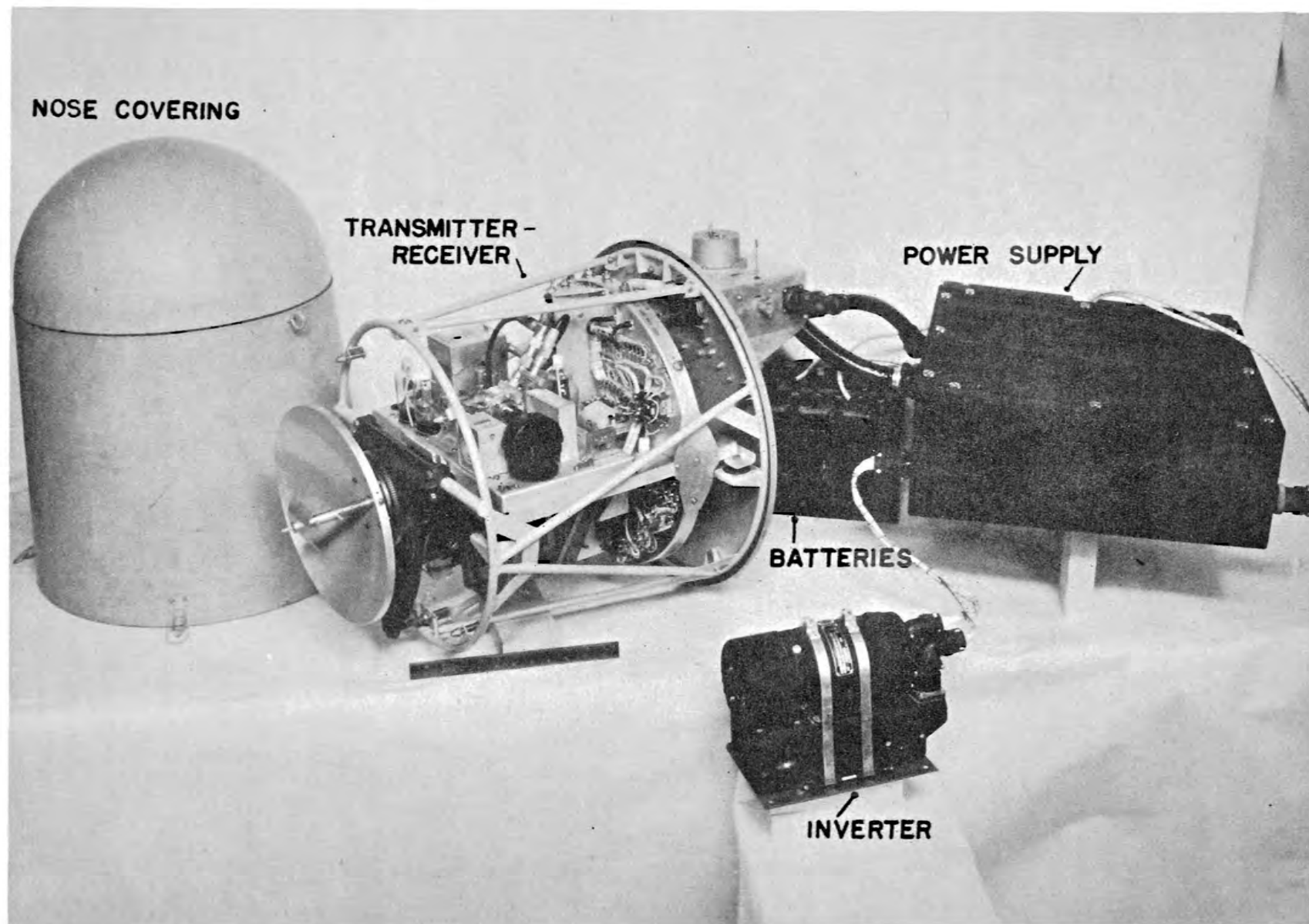


Figure 11 — SWOD Radar Mark 2 Model 1

fication of the 7-stage 1F amplifier is more than 100 decibels. The second detector is followed by a video amplifier whose output is fed into a tapped delay line which is a part of the target-selector circuit. The delay line supplies early, control, and late echoes to operate the target selector as previously described.

The junction box, housing the breakaway connector and time-delay switch, is mounted directly on the nose assembly.

The power is obtained from two 14-v batteries driving a 26.5-v input inverter with selenium disc regulator. The output is 115 v, 800 c, supplying regulated plate and bias voltages for the nose assembly.

The receiver characteristics of the SWOD Radar Mark 2, Mod 1, are substantially the same as those of the SWOD Radio Receiver Mark 1.

The two radar-homing devices just described were manufactured in substantial numbers together with the associated airplane control equipment and test equipment.

RADAR HOMING MISSILES AVAILABLE

Two series of missiles have been developed by the cooperative organization previously mentioned representing Division 5 of the National Defense Research Committee, the Bureau of Ordnance, Navy Department, the Massachusetts Institute of Technology, and the National Bureau of Standards. In addition, two missiles have been developed by the AAF Air Material Command to use the same radar-homing devices.

The Pelican series of missiles consists of glide bombs of three sizes using the SWOD Radio Receiver Mark 1, Mod 3, an RHB system. The gliders are controlled by elevons, i.e., wing flaps, which are moved together to control the path in a vertical plane and differentially to give banked turns. The aerodynamic design is such that the angle of attack is practically constant, independent of control position. This is accomplished by suitable tail and center of gravity locations which give moments on the tail due to changes in downwash from the wings to counter balance the moments produced by displacement of the flaps.

The following missiles have been developed:

<i>Designation</i>	<i>Wing Span</i>		<i>Total Weight</i> lb	<i>Pay Load</i>
	<i>ft</i>	<i>in.</i>		
Experimental	8	5	725	325-lb depth charge
SWOD Mark 7	8	5	900	500-lb bomb
SWOD Mark 8	10	—	1500	1000-lb bomb
	12	—	2600	2000-lb bomb

Tests of these missiles were quite successful, about 40% hits being secured on a Liberty ship from a range of 10 miles. The mean circular probable error for

a point target is about 150 ft. However, in view of the Bat development, which was nearly ready, decision was made not to use this type of missile in combat. RHB missiles require the releasing aircraft to make a steady 360° turn, while the radar operator keeps the target illuminated until the missile has struck. The Bat missiles are entirely self-contained and the releasing aircraft may take evasive action immediately after release. As previously pointed out, the range of Pelican is about twice that of Bat and hence the Pelican type may eventually be found useful.

The Bat series of missiles have the same airframes as Pelican with the SRB system SWOD Radar Mark 2, Mod 1. However, the SRB cannot be used in the smallest Pelican airframe of 8 ft, 5 in.-span. The following missiles have been developed:

<i>Designation</i>	<i>Wing Span (ft)</i>	<i>Total Weight (lb)</i>	<i>Pay Load</i>
SWOD Mark 9	10	1600	1000-lb bomb
SWOD Mark 10	12	2600	2000-lb bomb

The accuracy of Bat missiles is about the same as that of Pelican, the mean circular probable error being about 150 ft. Only a few of these missiles reached the combat area, but two ships are reported to have been sunk by their use.

The Army Air Forces applied the two devices to glide bombs of their GB series carrying a 2000-lb bomb, the one with RHB being denoted GB-7, and the one with SRB being denoted GB-14. These developments have proceeded with low priority and few tests have been made.

TREND OF FUTURE DEVELOPMENT

Experience with present radar-homing equipment and missiles suggests many directions for future development. Since there is great military interest in propelled missiles of supersonic speed and long range against air and ground targets, the homing device of the future will probably be intended to function only in the final stages of flight; the control during the earlier stages is by autopilot, some form of radar beam, or remote radio control. Present equipment would not function at all under such conditions, since it requires selection and locking on the target before release and continuous tracking in range. Two solutions suggest themselves: (1) radar repeat-back and control channels to permit remote target selection; or (2) an automatic target-seeking and selecting circuit which (a) can be kept inoperative during the early part of the flight, (b) can be made to search automatically in range beginning at any desired range, and (c) can be preset to give first, second, third, fourth, or fifth target in order of increasing range according to decision of the operator made on the basis of the early warning radar reconnaissance. The first solution is probably not applicable to high-speed missiles. Enough work has been done in the laboratory on the second solution to show that the circuits can be developed.

The radar-homing device of the future will probably use high-speed electrical switching rather than mechanical scanning. Thus it will be able to compare the

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amplitudes of successive pulses, reduce the effects of fading and also reduce the time lag of the system. If of the RHB type, synchronization will be accomplished by means of a stabilized audio-frequency oscillator in the missile. Steps will be incorporated to defeat countermeasures. The SRB type will use a separate antenna for transmitting so that the enemy cannot detect the scanning frequency in the transmitted signals. Automatic frequency shifting of transmitter and local oscillator simultaneously will make jamming exceedingly difficult. The equipment will probably operate at shorter wavelengths, probably in the neighborhood of 3 cm. In order to reduce the size and weight, the tubes and circuit techniques developed in connection with proximity fuses will probably be applied to radar-homing devices.

The servomechanisms will be much more rapid in action and have smaller time lag. Computers will be used to reduce errors arising from wind and target motion. The intelligence device will probably be of the automatically tracking type, its output being used on a servo system to keep its axis pointed at the target. Information for missile control will be derived from the angular displacement and speed of the axis of the intelligence device with reference to the missile axis.

It is important to note that much of this development can be carried out economically on glide bombs or on powered missiles of 500-mph speed. The Air Forces should undertake to see that development of radar-homing devices is continued along the lines indicated.